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Fluvial entrenchment and integration of the Sanmen Gorge, the Lower Yellow River

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ABSTRACT

Strategic studies of gravel deposits, in particular using heavy-mineral analyses, have thrown light on the important unresolved question as to the timing of the initiation of the Yellow River drainage through the Sanmen Gorge, which linked the headwaters of that system in the Fenwei Basin and further upstream with the North China Plain and the Pacific Ocean in the east. Survey of the Sanmen Gorge reach revealed previously unrecognized gravel levels: a higher fifth terrace (T5) and a gravel that formed on a high-level planation surface that is preserved on the flanks of the gorge, below the Xiaoshan upland. This high-level gravel differs markedly from the Yellow River terraces, with a lack of material from the upstream catchment, and would appear to represent a small fluvial catchment that developed in the area during the formation of the planation surface, before the Sanmen Gorge was excavated. Comparison was also made with basin-fill gravels from the endorheic fluvio-lacustrine system that existed immediately upstream of the gorge, and was captured by the Yellow River when the latter was cut, and with the modern bedload gravel of the Yellow River in this reach. The former contains significant quantities of unstable hornblende, which implies more local derivation for the endorheic system, whereas the modern bedload resembles the terrace gravels in showing compositional maturity and long-distance transport from upstream within the catchment. The work reinforces a minimum age of 1.2 Ma for the formation of the Sanmen Gorge.

Keywords: Yellow River; Sanmen Gorge; Gravel fabric; Heavy minerals; River terraces

1. Introduction

The Yellow River, one of the world's largest drainage systems, originates in the northeastern part of the Tibetan Plateau, and flows through a series of large-scale fault zones, orogenic belts and rift basins. Knowledge of its formation and evolution is essential for an understanding of the developmental history and structural changes of the East Asian landscape. In Western Henan, between Sanmenxia in the west and Xiaolangdi in the east, the Yellow River has deeply dissected the Xiaoshan upland to form the narrow Sanmen Gorge. Since the Xiaoshan represents the final barrier to be traversed by the river in its route to the Pacific (Wu et al., 1998; Jiang et al., 2005; Kong et al., 2014), the formation of the Sanmen Gorge is equated with the emergence of the modern Yellow River system. Thus, much research has been carried out to determine the origin of this gorge, which is linked with the former existence of the Sanmen palaeo-lake in the Fenwei Basin upstream (Wang et al., 1959). Some workers have suggested that the ancient lake persisted until 0.25–0.15 Ma, which would imply that the Yellow River did not cut the Sanmen Gorge, thus draining the lake, until that time (Wu et al., 1998; Wang et al., 2002; Ji et al., 2006; Jiang et al., 2007). However, study of the lacustrine strata at Wujiapu, Yancun, Songjiagou and Dongpogou has shown that sedimentation in the Sanmen palaeo-lake had already ceased by 1.8–1.1 Ma (Cao et al., 1985; Sun et al., 1988; Ge et al., 1991; Yue, 1996). In the Mangshan area, downstream of the gorge, the particle size and sedimentation rate of loess have both been higher since 0.25 Ma than in the central part of the Loess Plateau (Jiang et al., 1998, 1999; Wu et al., 1999; Ji et al.; 2004; Zheng et al., 2007; Prins et al., 2009). The main derivation of this coarser aeolian sediment is from the alluvium of the Yellow River, once the latter was flowing through the Sanmen Gorge (Ji et al.; 2004; Zheng et al., 2007). The results of recent zircon U-Pb tracer and cosmic radionuclide dating have revealed that the Sanmen Gorge was occupied by the Weihe River from 1.5 to 1.3 Ma, leading to the drainage of the Sanmen palaeo-lake and connection of the upper reaches of the Yellow River to the sea (Kong et al., 2014). In summary, there is still considerable disagreement about the timing of and processes involved in the formation of the Yellow River in Western Henan.

River terraces are abandoned parts of ancient river floodplains (Merritts et al., 1994; Bridgland, 2000) and, as such, provide the most direct evidence of drainage system development (Pan et al., 2005a). The composition and sedimentary structures of terrace gravel layers are also widely used to establish the flow direction and provenance areas of rivers (Rust, 1972; Sugai, 1993; Miao et al., 2008; Nie et al., 2015), of great value for reconstructing past drainage patterns (Yuan and Tao, 2008). Therefore, this paper will first explore the geomorphology of the system along the Yellow River in Western Henan, with re-evaluation the regional river terrace sequence. Second, we will analyze and compare the characteristics of heavy minerals, lithology, and sedimentary structures of terrace gravel layers. From these data, which supplement previously published results, we will reconstruct the formation of the Yellow River in Western Henan.

2. Regional geological and geomorphic setting

During the Cenozoic, the collision of the Indian and Eurasian plates progressed, leading to left-lateral fault movement at the northern edge of the Qinling Mountains (Tapponnier and Molnar, 1977). The north China plate experienced tensile stress-based movement, resulting in the NE–SW alignment of the crescent-shaped Fenwei Basin (Tapponnier et al., 1982; Peltzer et al., 1985) in which the large Sanmen palaeo-lake developed. At its largest the lake extended north to Yumenkou, south to the Qinling Mountains, west to cover Baoji and in the east it reached Sanmenxia (Fig. 1A). On the whole, this palaeo-lake was isolated from the North China Plain by the Xiaoshan Mountains, which consist mainly of Proterozoic quartz schist and andesite, Carboniferous quartz sandstone and andesite, Permian sandstone and shale, and Triassic shale and sandstone (Ministry of Geology and Mineral Resources of the People’s Republic of China, 2000). Fluvial and lacustrine sediments that accumulated in the Fenwei Basin during the period from 5.3 to 0.15 Ma are classified as the

Sanmen Formation (Jiang et al., 2007), which is divided into lower and upper parts. The lower Sanmen Formation is composed of gravels and sand, whereas the upper is characterized by sand and clay with a minor gravel component (Sun et al., 1988).

A characteristic planation surface occurs on the flanks of Yellow River valley in Western Henan, comparable with the well-known planation surface of the Tangxian period in the middle reaches of the Yellow River (cf. Pan et al., 2012; Xiong et al., 2017). In the Fenwei Basin, the lower Sanmen Formation was directly exposed at the edge of the basin. We can observe in the field that its top surface is about 500 m high, roughly at the same level as the planated area of bedrock surrounding this basin, suggesting correlation between the lower Sanmen Formation and the planation surface (Hu et al., 2017). Along the Sanmen Gorge, the planation surface is disrupted at each end of the gorge by a normal fault (Fig. 1B). Its altitude increases considerably at first and then is gradually reduced toward the downstream end of the gorge, finally fading out into the North China Plain. The deformation of the planation surface reflects the marked uplift of the Xiaoshan relative to the Fenwei Basin and the North China Plain. Moreover, along the eastern front of this mountain range, a deposit of river gravel that sits on the lower levels of the planation surface is deformed with the underlying planated bedrock and can thus be regarded as a component of this surface. Referred to as ‘G’ (Fig. 4a), this represents a river that originated from the eastern front of the Xiaoshan upland and flowed downstream into the North China Plain toward the end of the period of planation. Despite similar roundness and sorting characteristics, the clast composition of gravel ‘G’ shows significant differences in comparison with the Yellow River terrace deposits. Thus, the river represented by ‘G’ is interpreted here as pre-dating the Yellow River in its modern form; it is suggestive of the initiation of the incision that led to basin inversion and may be the earliest development of the stream that was to become the Yellow River.

<Fig.1 is hereabout>

Several fluvial terraces were formed by the Yellow River during its incision into the upper Sanmen Formation. Terrace sequences are well developed at the entrance to the Sanmen Gorge (Sanmenxia), in the middle part of the gorge reach (Dongcun), in its lower reaches (Xiaolangdi), and at its downstream end (Kouma) (Fig. 2A). At Sanmenxia, a fluvial sequence of four terraces was established for the first time by Pan et al. (2005b). However, following further field investigation here, a higher terrace (T5) was identified above the stacked basin-fill sequence and extending downstream along the Sanmen gorge (Pan et al., 2005a; Fig. 2B). Now this terrace, classified T5, has been confirmed as being well preserved at Dongcun, Xiaolangdi, and Kouma (Hu et al., 2017). In general, the widely accepted geomorphic sequence of the Yellow River in Western Henan is characterized by a high-level planation surface and five fluvial terraces (Kong et al., 2014; Xiong et al., 2017). With reference to elevation, overlying loess stratigraphy, and reconstruction of terrace treads, Hu et al. (2017) have made a detail correlation of the geomorphic sequences occurring at the various sites along the study reach (Table 1). Notwithstanding this work, however, there are still no data from which to describe and discuss the composition and sedimentary structures of the gravels accumulated on these terrace levels and within the Sanmen Formation, which will be essential to make further progress in understanding the processes involved in the formation of the Yellow River.

<Fig.2 is hereabout> <Table 1 is hereabout>

3. Methods

3.1. Provenance analysis based on heavy-mineral composition

Different parent rocks can have unique mineral signatures, leading to distinguishable mineral assembles obtained from sediments with disparate origins (Zhao and Liu, 2003; Yue, 2010; Garzanti et al., 2013). Based on the combined characteristics of heavy minerals, therefore, the provenance of fluvial sediments can be analyzed and traced. In addition, owing to the difference in weathering resistance of heavy minerals, less stable minerals will be progressively removed from sediments, thereby enhancing the content of resistant minerals with increasing transport distance. The provenance direction and distance of transport can be thus established by analyzing the variation in content of resistant heavy minerals (Mange and Maurer, 1992; Garzanti et al., 2008; Zhou et al., 2010). In this type of analysis, a ZTR index is defined, which is the percentage composition of zircon, tourmaline, and rutile (Hubert, 1962); this index is generally employed to reflect transport distance with higher values implying longer distance, and vice versa (Fu et al., 2013). Another method, Q-type cluster analysis, is also widely used in provenance analysis and stratigraphic correlation (Wu et al., 1996; Malone, 2007; Zhang et al., 2013), based on the similarity in relative percentages of heavy minerals obtained from tested samples (Ding et al., 2010).

3.2. Sampling and pretreatment for heavy mineral analysis

Samples for heavy-mineral analysis were collected from the upper Sanmen Formation, from terrace sediments, and from gravel 'G' on the planation surface. In order to avoid disturbance and contamination, natural outcrops were cut back to expose fresh river sediments. A total of 8 fluvial sand samples were obtained (Table 2): from terrace T5 at Sanmenxia (SMXT5; Fig. 3B), terrace T5 at Dongcun (DCT5), terrace T4 at Xiaolangdi (XLDT4) and terrace T3 at Kouma (KMT3; Fig. 3C), plus two samples from the modern channel of the Yellow River (SMXRB1 and SMXRB2; Fig. 3D), one from gravel 'G' at Xiaolangdi (XLDG) and one from the upper Sanmen Formation (HX ;Fig. 3E).

<Table 2 is hereabout>

Heavy-mineral extraction and identification was performed in the Institute of Geology and Mineral Resources of the Hebei Province. All the samples were first sieved to isolate the 63–125 μm fractions and then elutriated in distilled water to remove the light components. The remainder were further separated and purified within a 2.89 g/cm^3 dense solution (bromoform) using a separatory funnel. After repeated flushing with alcohol, the heavy components were dried fully at the constant temperature of 60 °C and spread on a glass sheet for magnetic separation. They were divided into magnetic and nonmagnetic heavy minerals, and weighed respectively. For each sample, a random 300 grains (minimum) on a glass slide were identified by microscope (Olympus SZX12) from each of the magnetic and nonmagnetic fractions, whereby the mass percent of each heavy mineral could be calculated.

<Fig. 3 is hereabout>

3.3. Fabric structure and lithology

The fabric structure of a gravel deposit is defined here as the statistical ‘a–b’ plane orientation presented by its pebbles (Zhao, 1985). In fluvial deposits gravel clasts are generally imbricated with dip azimuth opposite to flow direction (Rust, 1972). The imbricated plane of each pebble is expressed as the ‘a–b’ plane, in which ‘a’ and ‘b’ refer to the long and short axes respectively. Within a slowly flowing river, the long axis of ‘a’ is roughly aligned perpendicular to flow direction, while it is usually parallel to flow direction in a rapidly flowing river. The direction and velocity of palaeocurrent flow can thus be reconstructed by measuring the dominant dip directions of the a–b planes and long axes of selected pebbles (Chen et al., 2008).

Gravel deposits are accumulated via erosion, transport, and sorting, and finally consist of pebbles that differ in chronology and lithology (Zhu et al., 2002). Their lithological composition is widely regarded as an indicator for provenance determination and terrace correlation (Bridgland, 1986). On the basis of these results, the drainage area and its evolution can be reconstructed (Miao et al., 2010).

3.4. Fabric measurement and lithological distribution

Fabric measurement was only undertaken on outcrops of sediments that were not deformed, weathered or otherwise disturbed (Fig. 4a). For each outcrop > 100 pebbles with long (a) axis > 6 cm were selected for measurement. The software PC99 (Stewart et al., 2001) was used to calculate vector mean directions (a axis and a–b plane), which can be regarded as river flow directions (Fig. 4b).

Gravel clast lithology was determined for > 100 pebbles within a quadrat applied to deposits selected for lithological study; the quadrat was of 5 m width and covered the full thickness of the selected gravel layer. Fresh surfaces (of diameter > 5 cm) broken by geological hammer were used for lithological identification. On this basis the proportions of different lithologies within the investigated gravels could be approximated (Fig. 4b).

<Fig. 4 is hereabout>

4. Results

4.1. Heavy-mineral analysis and comparison

Heavy-mineral data from the eight fluvial sand samples are listed in Table 3. Some 19 different heavy minerals were identified, of which hornblende and pyroxene, unstable in fluvial bedload and post-depositional environments (e.g., Peng et al., 2016), and stable rutile, zircon, tourmaline, anatase, monazite, apatite, garnet, staurolite, ilmenite and magnetite appear in most of the samples. In contrast, pyroxene, anatase and pyrite were encountered in only a few samples.

<Table 3 is hereabout>

Based on the distribution pattern of these heavy minerals (Fig. 5), samples SMXT5, DCT5, XLDT4 and KMT3, taken from the uppermost terraces, can be seen to form a separate grouping. They are all rich in garnet, red limonite, ilmenite and magnetite, as well as many other heavy minerals. The heavy-mineral signature in these four samples can therefore be expressed as 'garnet + red limonite + ilmenite + magnetite + hornblende', in terms of their average contents. The heavy mineralogy of the two samples from the current riverbed (SMXRB1 and SMXRB2) is dominated by garnet, which is particularly high (reaching up to 32–40 %), red limonite and ilmenite. Thus they have a consistent 'garnet + red limonite + ilmenite + magnetite + hornblende' heavy mineralogy. Sample XLDG, from gravel 'G' (on the planation surface), yielded a 'red limonite + ilmenite + magnetite + garnet' heavy-mineral signature. Compared with other samples, it has a low garnet content and a high proportion of combined opaque minerals (red limonite, ilmenite and magnetite), up to 82 %. Sample HX, from the upper Sanmen Formation, can be characterized as 'hornblende + garnet + red limonite + magnetite', in which the content of hornblende reaches up to 64 %, implying a greater proportion of unstable minerals. Borehole data from the upper Sanmen Formation also suggest a high hornblende content (more than 40 %: Huang, 1981), in general agreement with our result.

<Fig. 5 is hereabout>

A ZTR index of 3.17 has been calculated for samples SMXRB1 and SMXRB2 (Table 3). Given that the bedload sediments of the lower Yellow River have generally experience long-distance transport and are well sorted, this figure can be employed as a reference for the evaluation of the transport distance and sorting of the other fluvial deposits. The average ZTR index for the group of samples SMXT5, DCT5, XLDT4 and KMT is 6.35, considerably higher than that (3.17) for the current Yellow River bedload. Moreover, the content of stable garnet in these samples is significantly higher than that of unstable hornblende. All these comparisons imply that the highest Yellow River terrace sediments have been transported over long distances. In contrast, the ZTR index of sample XLDG, from gravel 'G', is only 1.50, significantly lower than that of the modern riverbed sediments. The garnet component is only 5.19 %, significantly lower than that (32.29–39.43 %) of the current Yellow River sediments.

These remarkable differences suggest that the gravel on the planation experienced only short-distance transport, probably originating from the eastern front of the Xiaoshan Mountains. The ZTR index of sample HX (from the upper Sanmen Formation) is just 0.55, even further below than that of the Yellow River bedload; this, coupled with its high proportion (64.04 %) of unstable hornblende, probably reflect the nearby provenance and rapid deposition of this basin-fill sediment.

On the basis of above heavy-mineral data, the eight fluvial sand samples in Fig. 6 can be divided into three categories using the Average Intra-group Connection and Squared Euclidean Distance methods (Du and Jia, 2009). Type Ⅰ includes the riverbed-sediment samples (SMXRB1 and SMXRB2) and the uppermost terrace samples (SMXT5, DCT5, XLDT4, and KMT3). Their heavy-mineral signature appears similar, characterized by high garnet content and high ZTR index. Sample XLDG (gravel 'G') has a rather lower ZTR index than other types, forming a separate category Ⅱ. The remaining sample (HX), from the upper Sanmen Formation, again represents a separate category (Type Ⅲ), arising from its relatively high unstable hornblende content and its low ZTR index.

<Fig.6 is hereabout>

4.2. Paleocurrent analysis and lithological comparison

The results of these analyses of the gravels of the planation surface and terrace sequence at Xiaolangdi are presented in Fig 4b. The orientations of 'a–b' plane and 'a' axis appear to coincide, implying that these gravels were probably deposited by fast–flowing rivers, which corresponds with the current hydrological characteristics in the Sanmen Gorge. The implied paleocurrents are approximately directed SE, opposite to the orientations (which arise from clast imbrication), and roughly agreeing with the flow direction of the Yellow River in Western Henan (Fig. 2A), an exception being the gravel of terrace T3. This latter inconsistency may be attributed to the meandering of the river during the formation of this terrace.

The clast lithology of these gravels shows a dominance of quartz sandstone (Fig. 4b). Compared with gravel 'G', however, the gravels of terraces T4, T3, T2, and T1 are richer in quartz sandstone, granite, and quartzite, and also in metamorphic andesite, basalt, and limestone. Further analysis also finds that the non-quartz sandstone in these gravels has increased progressively and substantially, such that they are characterized by a polymict composition. In general, the data show that the gravels of progressively lower terraces have correspondingly more complex clast lithologies, despite a lack of granite in the T2 and T1 deposits due to deep fluvial incision refusing this kind of gravels input from granite bedrock on top valley. Its significant difference in lithological composition suggests that gravel 'G' (on the planation surface), is the product of a local stream rather than the Yellow River.

5. Discussion

The higher terrace gravels at various locations along the Yellow River valley in Western Henan (samples SMXT5, DCT5, XLDT4, and KMT3) show similar heavy-mineral assemblages, and yield ZTR indices higher than those from the modern Yellow River bedload. Cluster analysis based on heavy-mineral distribution groups the terrace gravels together with modern riverbed sediments, such that at the Sanmen Gorge, in its central and downstream parts and further downstream, Yellow River terrace deposits are comparable with modern river sediments in this respect (Fig. 6). This conforms with the clast-fabric data, which are also generally in keeping with formation of the terrace deposits by the Yellow River (Fig. 4b). The sample from gravel 'G' (XLDG) shows a low garnet content and a low ZTR index in comparison with the modern Yellow River bedload and the sampled terrace gravels. These differences suggest a short transport distance and relatively fast sedimentation for this planation-surface gravel. Although fabric analysis revealed that this gravel layer was laid down by eastward-flowing drainage, consistent with the Yellow River, we speculate that it represents the sediment from a local river at the foot of the Xiaoshan upland, emplaced during the development of the planation surface.

The heavy-mineral characteristics of the upper Sanmen Formation (HX) also differ from those of the Yellow River terraces (samples SMXT5, DCT5, XLDT4, and KMT3) and modern bedload (samples SMXRB1 and SMXRB2). Compared with the bedload sediments, sample HX has a higher hornblende content and lower ZTR index, indicating a shorter transport distance and more rapid sedimentation rate, reflecting the accumulation of predominantly near-source material at the edge of the Fenwei Basin. Furthermore, cluster analysis places the HX and XLDG heavy-mineral samples into different groupings (Fig. 6), which is consistent with separate drainage systems being represented, before the connection of the Fenwei Basin with the downstream system by the cutting of the Sanmen Gorge. The clear implication is that there was no Sanmen Gorge at that time, with the Yellow River not yet established in Western Henan.

From the evidence obtained, and with reference to terrace projection and reconstruction, the higher terrace gravels at Sanmenxia, Dongcun, Xiaolangdi, and Kouma can be correlated, despite having different terrace number at these sites, suggesting an initial level of the Yellow River valley floor after entrenchment along the Sanmen Gorge (Fig. 2B). In the upper (Sanmenxia) and lower (Kouma) reaches of the Sanmen Gorge, the highest Yellow River terraces have been determined as coeval, at 1.2 Ma (Pan et al., 2005a; Hu et al., 2017). Therefore, we can deduce that the Sanmen Gorge had been formed, thus establishing the Yellow River in its modern form in this region, by 1.2 Ma. Once formed, this river transported considerable material from its middle and upper reaches onto the North China Plain. There are further points that are conformable with our data. First, from the analysis of borehole data in the eastern part of Henan Province, Liu et al. (1988) have argued that fluvial deposition by the Yellow River on the North China Plain began in the Early Pleistocene. The geochemical similarity between the early sediments of the upper Yellow River Delta and the composition of modern Yellow River deposits also indicates that the Yellow River flowed to the sea in the Early Pleistocene (Yang et al., 2001). In the early Middle Pleistocene, many of the same species of fossil ostracods occur in the Fenwei Basin and in the sediments of the North China Plain, revealing probable drainage linkage before that time (Xue, 1996). The continental sediments of Bohai Bay are mainly from the Yellow River catchment (Saito et al., 2000), and their deposition rate increased rapidly after 1.0 Ma (Xiao et al., 2008; Yao et al., 2012), which may be further evidence that the Sanmen Gorge had been formed by that time, allowing material from the middle and upper reaches of the Yellow River to reach the sea. Recently, borehole data from the northern part of the Fenwei Basin has revealed that, since 1.0 Ma, alluvial-fan sediments have been mixed with shallow lacustrine deposits there (Rits et al., 2016), indicating that the northern part of the basin was separated from the deep-lake facies depositional environment by that time, which is close to the age of Sanmen Gorge formation suggested above.

This pattern of landscape evolution, in which ancestral lake basins were disrupted and replaced by fluvial drainage, also occurred in other continental interior regions worldwide (e.g., Demir et al., 2018). In the eastern Anatolian Plateau, the integration of the modern River Euphrates was associated with the disruption of paleolake basins in the Mid-Pleistocene (Seyrek et al., 2008; Westaway et al., 2008; Demir et al., 2009). In the central-southern USA, due to fluvial entrenchment into the Rio Grande Rift, a paleolake basin was disrupted, resulting in the integration of the modern Rio Grande River with its upper reaches in the Mid-Pleistocene (Westaway, 2009). Indeed, numerous similar examples of 'invertion' of fluvio-lacustrine basins at around the Early – early Middle Pleistocene have been reported with suggested linkages to changes (greater cooling) of global climate and patterns of climatic fluctuation (e.g., Matoshko et al., 2004; Bridgland and Westaway, 2014; Bridgland et al., 2017; Cunha et al., 2017; Maddy et al., 2017).

6. Conclusion

The high-level gravel 'G', deposited on the planation surface along the eastern front of the Xiaoshan upland, represents a river that drained eastward into the North China Plain. It differs from Yellow River and Sanmen palaeo-lake sediments in heavy-mineral composition and gravel lithology, suggesting that it was a river of local derivation. Under the constraint of the previous chronological framework for the planation surface and the highest Yellow River terrace in Western Henan, the excavation of the Sanmen Gorge and resulting integration of the Yellow River with its upper and middle reaches occurred at 3.6–1.2 Ma. Further heavy-mineral analysis implies that the endorheic fluvio-lacustrine system existing immediately upstream of the gorge was probably captured by this local river when the latter was entrenched.

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Figure Captions

Fig. 1. Map and topographic profile along the Yellow River from Sanmenxia to Xiaolangdi. (A) major faults, rivers, mountains, and basins along this reach of the Yellow River. The extent of the Fenwei Graben is outlined by the white transparent overlay. The Yellow River incises into the Xiaoshan Mountains, forming the Sanmen Gorge, which is constrained by normal faults. The inset map shows the location within China. (B) maximum, mean, and minimum topography along the Sanmen Gorge. Active faults and the interpreted longitudinal profile of the planation surface are also depicted. The planation level along the Sanmen Gorge has been deformed by normal faults.

Fig. 2. Geomorphic transects and their locations. (A) map of the study region showing topography (using the same data source as Fig. 1), active faults, and field sites of the geomorphic transects (see Fig. 1 for location). (B) the details of these geomorphic sections. Their location is presented in A with the corresponding sequence number. P = planation surface; T = fluvial terrace; G = gravel layer accumulated on the planation surface.

Fig.3. Field photos of geomorphic surfaces and heavy-mineral sampling sites at Sanmenxia. (A) fluvial terrace sequence and the planation surface at Sanmenxia. (B) the uppermost terrace T5 and the sampling site of SMXT5 at Sanmenxia. (C) the uppermost terrace T3 and the sampling site of KMT3 at Kouma. (D) the river bed and sampling site of SMXRB1 within the Sanmen Gorge. (E) the sampling site of HX in the stratigraphy of the upper Sanmen Formation.

Fig. 4. Fabric and clast-lithology data for the gravel layers at Xiaolangdi. (a) the geomorphic sequence at Xiaolangdi. Inset photograph shows the gravel layer (G), accumulated on the planation surface. (b) Rose diagrams and pie charts showing fabric and clast-lithological data. The red arrows indicate paleocurrent directions.

Fig. 5 Histograms of the heavy-mineral content of the various samples.

Fig. 6 Dendrogram (Q-type cluster analysis), based on the similarity in relative percentages of the heavy minerals. For details of this method, refer to Ding et al. (2010).

Table 1. Fluvial terrace correlation between Sanmenxia and Kouma

Site			Terrace 1	Terrace 2	Terrace 3	Terrace 4	Terrace 5	Planation surface					
Name	Co-ordinates	H_o (m)	H (m)	h (m)	H (m)	h (m)	H (m)	h (m)	H (m)	h (m)	H (m)	h (m)	H (m)
Sanmenxia	34°48′06″N, 111°14′25″E	306.6	317.2	0	325.5	2.0	338.0	4.0	382.1	2.0	394.1	2.0	557.8
Dongcun	34°50′46″N, 111°34′07″E	249.5	261.9	0	270.3	3.9	300.5	2.3	325.0	0.6	427.0	0.4	647.0
Xiaolangdi	34°55′15″N, 112°23′58″E	133.8	142.3	3.1	NO	NO	193.5	3.9	229.9	3.6	291.7	5.8	381.4
Kouma	34°49′20″N, 112°46′18″E	89.8	99.8	0	NO	NO	115.0	0	NO	NO	145.0	0	200.0

For each site, H_o denotes the height of the Yellow River above sea level. For each river terrace and for the planation surface, H denotes height above sea level and h denotes the thickness of fluvial sediments (h=0 denoting sites where the terrace surface is cut into bedrock). NO denotes river terraces that are not observed at particular sites.

Table 2. Sampling information of heavy minerals

Lab code.	Co-cordinates	Source	Size
SMXT5	34°48′06″N, 111°14′25″E	Sand lens within T5 gravel at Sanmenxia	coarse sand mixed with fine gravels
DCT5	34°50′46″N, 111°34′07″E	Sand lens within T5 gravel at Dongcun	coarse sand mixed with fine gravels
XLDT4	34°55′15″N, 112°23′58″E	Sand lens within T4 gravel at Xiaolangdi	coarse sand mixed with fine gravels
KMT3	34°49′20″N, 112°46′18″E	Sand lens within T3 gravel at Kouma	coarse sand mixed with fine gravels
SMXRB1	34°55′15″N, 111°23′58″E	Sand layer within the Yellow River bedload at Xiaolangdi	coarse sand mixed with silt and clay
SMXRB2	34°50′46″N, 111°34′07″E	Sand layer within the Yellow River bedload at Dongcun	coarse sand mixed with silt and clay
XLDG	34°53′20″N, 112°20′51″E	Sand lens within gravel layer G, the planation surface at Xiaolangdi	coarse sand mixed with fine gravels
HX	34°52′24″N, 111°12′50″E	Sand layer within the upper Sanmen Series	coarse sand mixed with silt

Table 3. Heavy mineral composition (%) and ZTR indexes of these samples from table 2

Minerals	SMXRB1	SMXRB2	SMXT5	DCT5	XLDT4	KMT3	XLDG	HX
Zircon	1.80	1.65	4.52	13.69	2.19	1.85	0.83	0.22
Apatite	4.78	0.31	0.37	0.38	0.32	0.06	0.88	0.03
Rutile	0.97	0.26	0.68	0.78	0.49	0.18	0.26	0.10
Garnet	39.43	32.29	10.26	15.63	44.13	57.80	5.19	10.71
Tourmaline	1.50	0.16	0.46	0.16	0.39	0.01	0.41	0.23
Monazite	0.00	0.10	0.14	0.00	0.00	0.00	0.00	0.00
Sphene	0.88	0.33	0.42	0.63	0.00	0.11	0.63	0.00
Zoisite	0.00	0.00	7.71	0.63	0.00	0.56	0.25	0.03
Silimanite	0.00	0.00	1.66	0.00	0.35	0.03	1.81	0.02
Allochite	4.76	0.82	8.93	4.03	1.31	1.42	2.56	0.12
Hornblende	12.30	1.53	25.60	3.91	0.12	0.22	0.00	64.04
Staurolite	0.01	0.18	0.00	0.00	0.00	0.00	0.00	0.00
Pyroxene	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Anatase	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00
Leucoxene	2.44	1.14	1.58	0.66	0.52	0.13	0.25	0.05
Pyrite	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00
Ilmenite	8.88	14.32	4.84	23.44	24.87	8.58	29.48	1.94
Hematite and Limonite	11.82	40.53	16.42	15.88	13.35	19.16	43.33	7.49
Magnetite	1.33	3.37	7.25	14.84	8.25	1.13	9.38	7.68
Others	9.04	3.00	8.97	5.17	3.70	8.75	4.73	7.33
ZTR index	**4.27**	**2.07**	**5.66**	**14.63**	**3.07**	**2.04**	**1.50**	**0.55**

Highlights

- The gravel layer accumulated on the planation surface along the eastern front of the Xiaoshan represents a local river.
- The sediments by this local river are different from the gravel layers of the Yellow River terraces and the upper Sanmen Formation.
- The Sanmen paleolake within the Fenwei basin was finally disrupted by the westward capture of this local river.
- The Sanmen Gorge was excavated by this local river cut-through the Xiaoshan separating the Fenwei basin and the North China Plain.
- The integration of the Yellow River may be attributed to the remarkable sea-level fluctuation starting in the Mid-Pleistocene.